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Differential vergence movements in reading Chinese and English:

Greater fixation-initial binocular disparity is advantageous

in reading the denser orthography

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Abstract

We explore two aspects of exovergence: we test whether smaller binocular fixation disparities accompany the shorter saccades and longer fixations observed in reading Chinese; we test whether potentially advantageous psychophysical effects of exovergence (cf. Arnold & Schindel, 2010; Kersten & Murray, 2010) transfer to text reading. We report differential exovergence in reading Chinese and English: Chinese readers begin fixations with more binocular disparity, but end fixations with a disparity closely similar to that of the English readers. We conclude that greater fixation-initial binocular fixation disparity can be adaptive in the reading of visually and cognitively denser text.

Keywords: eye-movements; reading; English; Chinese; fixations; vergence

Differential vergence movements in reading Chinese and English:

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Introduction

In recent decades, corpus analyses of reading behaviours have complemented the classic experimental paradigms pioneered by Rayner and colleagues (Rayner, 1998; Rayner, Pollatsek, Ashby, & Clifton, 2012). In the current study, we use crosslinguistic comparison of Chinese and English to elucidate the role of binocular eye-movements within fixations. Chinese is visually more complex than English and presents the reader with different ranges of problems within what may be universal reading behaviours (cf. Liversedge, Drieghe, Li, Yan, Bai, & Hyönä, 2016). Vision has been seen in general terms as a sequence of spatially and temporally conjugate movements (saccades) of the two eyes between static fixations. However, researchers using non-reading tasks have increasingly found departures from this simple picture, discovering asynchronies between the two eyes (e.g. Cornell, Macdougall, Predebon, & Curthoys, 2003; Enright, 1998) and movement within fixations (e.g. Engbert & Kliegl, 2004; Martinez-Conde, Macknik, & Hubel, 2000, 2004; Martinez-Conde, 2007; Simon, Schulz, Rassow, & Haase, 1984; Spauschus, Marsden, Halliday, Rosenberg, & Brown, 1999; Thiel, Romano, Kurths, Rolfs, & Kliegl, 2008). Our approach has been to explore normal (i.e. binocular) reading to try to understand *disjugacy*—how it might be adaptive for the two eyes to behave differently rather than strictly duplicating each other's efforts. Below we look at the role of the two eyes in vergence during reading.

The eyes *converge* to look at nearer objects and *diverge* to look at more distant objects; thus, degree of vergence is a robust source of depth information. When the

eyes are converging, the intersection of the lines of sight from the two eyes draws closer to the reader (Fig. 1). When the eyes are diverging, that point moves farther away from the reader. The intersection of the two lines of sight defines a point on the (ideal) geometric *horopter*, a sphere that includes the optical centres of the two eyes (Fig. 2); points on the (psychologically real) ‘empirical horopter’ define *corresponding points* projecting on the two retinas. An object farther away from the viewer than the horopter has an *uncrossed retinal disparity*: the viewer has to uncross (diverge) their eyes to fixate on it; it lies further to the right from the right eye’s line of sight than from the left eye’s line of sight. An object closer than the horopter has a *crossed retinal disparity*: the viewer has to cross (converge) their eyes to fixate on it; it lies further to the left from the right eye’s line of sight.

These optometric terms need to be distinguished from an unfortunately similar terminology in eye-movements-in-reading research, in which a *crossed fixation disparity* has the right eye (RE) fixating on the text to the left of the left eye’s (LE) fixation, and an *uncrossed fixation disparity* has the RE fixating on the text to the right of the LE’s fixation (Liversedge, White, Findlay, & Rayner, 2006). *Retinal disparity* is typically discussed in qualitative terms with respect to binocular fusion; *fixation disparity* (FD) describes the size and direction of any offset between the concurrent fixation points of the two eyes on the text—any departure from conjugate fixations by the two eyes. Both disparities concern the departure from hypothetical ‘corresponding points’ on the retinas.

Divergence causes the point at which the two lines of sight intersect (i.e. on the horopter) to move *away* from the reader. Note that this relationship holds for both crossed (right eye’s fixation to the left of the left eye’s) and uncrossed (right eye fixation to the right of the left eye’s) FDs. Divergence of the eyes reduces a crossed

FD and increases an uncrossed FD, and sometimes turn a crossed FD into an uncrossed FD. Convergence of the eyes reduces an uncrossed FD and increases a crossed FD, and sometimes turns an uncrossed FD into a crossed FD.

The plane of the text can be in front of the horopter (i.e. nearer the reader), on the horopter, or behind the horopter; these positions correspond to uncrossed FDs, conjoint fixations, and crossed FDs, respectively.

Over the last decade and more, researchers have observed that crossed FDs are elicited more by Eyelink technology, and uncrossed FDs by Dual Purkinje technology. Shillcock, Roberts, Kreiner and Obregón (2010) theorize that this difference is explained by the visually more challenging viewing conditions required by Dual Purkinje technology (light text on a dark screen, in a dark room) compared with Eyelink technology (dark text on a light screen, in normal room lighting). The best way to improve the incoming visual information is to fuse the input to the two eyes (Jones & Lee, 1981) and this fusion is facilitated by diverging the eyes so that the intersection between their two lines of sight falls (virtually) behind the plane of fixation, placing the text *inside* the horopter. (This theoretical position is based on developmental, neurophysiological and behavioural differences between processing the two types of FD; for further details, see Shillcock, et al. 2010. Kirkby, Blythe, Drieghe, Benson and Liversedge, 2013, suggest, on the basis of an empirical comparison of the two technologies, that variability in reports of crossed/-uncrossed FDs is attributable to viewing conditions such as luminance and viewing distance.) This ease-of-fusion explanation for directional differences in FDs in reading is relevant to the qualitatively (crossed vs. uncrossed) relatively stable spatial relationship between the two eyes' fixation points during any one particular text-reading event. A further claimed advantage of crossed FDs is the overlapping of a

privileged contralateral projection from text to cortex for each eye (see Obregón & Shillcock, 2012; Shillcock et al., 2010).

Can we extend this theorizing about the nature of vergence movements? We explore two lines of inquiry.

The first begins with the conventional view that vergence is centrally concerned with precision of binocular fixation. Early studies of reading were conflicting as to whether the eyes converge (Schmidt, 1917) or diverge (Clark, 1935; Taylor, 1966), but later studies show reduction of FD (e.g. Blythe et al., 2006; Hendriks, 1996; Kirkby et al., 2013; Liversedge, White, Findlay, & Rayner, 2006; Nuthmann & Kliegl, 2009), although such studies also all report a full range of convergent and divergent eye movements in fixations, with variation between participants (e.g. Hendriks, 1996; Jainta & Jaschinski, 2010) and with substantial variation in proportions of crossed and uncrossed FDs. Note that *divergence* in a crossed FD *reduces* the disparity. Reduction of FD during fixation has generally been seen as adaptive in avoiding diplopia (Holmqvist et al., 2011, p. 24), and most studies reveal *overall* absolute reduction of FD during fixations. Note that there can be substantial tolerance for absolute disparity between the two retinal images (Erkelens & Collewijn, 1985; see, also Cornell et al., 2003, for the absence of diplopia accompanying FDs in natural viewing conditions).

What vergence behaviours might we see in the two orthographies we study? Although there are difficulties in comparing Chinese and English—the two orthographies are pervasively different—saccades are reported to be shorter in Chinese and fixations longer (Liversedge et al., 2016). The logographic content of Chinese means denser visual variety and cognitive content compared with English. We may assume that reading Chinese elicits more precise targeting, with slower

vergence and more co-contraction of muscles (Hendriks, 1996), and we might predict correspondingly smaller FDs at the start of fixation. Juhasz, Liversedge, White and Rayner (2006) report no effect of the visual property of AlTeRnAtInG cAsE on the size of the FD. However, Jainta, Jaschinski and Wilkins (2010) report smaller minimum FD during fixation of text in which similarity in shape between the neighbouring strokes of component letters, as measured by the first peak in the horizontal auto-correlation of the images of the words (i.e. ‘stripey’ words are more demanding to process); they do not distinguish between the crossed (36%) and uncrossed (12%) FDs. In summary, some aspects of visual complexity of the orthography may well affect size of FD. The default assumption is that Chinese readers will produce smaller FDs from the beginning to the end of fixation.

Our second line of investigation concerns the fact that the eyes diverge to fixate more distant objects. Whether the FD is crossed or uncrossed on the plane of fixation, the eyes still *diverge* to fixate a yet more distant object. (For clarity, we will only refer to the FD as increasing or reducing, not to it “converging” or “diverging”.) What behaviours are associated with perceiving distant objects compared with proximal objects?

Images of objects that *appear* to be farther away are (surprisingly) processed more accurately (Arnold & Schindel, 2010; see Kersten & Murray, 2010, for a history of the ‘Aubert–Förster phenomenon’): given two optician’s charts, a small one in one’s hands and a large one on the wall, *both subtending the same retinal angle*, we are better at reading the one on the wall. The brain seems to invoke *constancy*: it uses contextual distance cues so as to scale perception, such that distant large things do not seem so small as their optical images might suggest. As Wheatstone originally showed, using prisms, the vergence angle of the eyes is a powerful cue to distance.

Arnold and Schindel (2010) manipulated this angle to vary illusory size and found that visual sensitivity (specifically orientation discrimination, *not* low contrast discrimination) improved for apparently larger stimuli. As Kersten and Murray (2010) point out, recent imaging research demonstrates V1 mediation of illusory size perception (Murray, Boyaci, & Kersten, 2006; Fang, Boyaci, Kersten, & Murray, 2008): the spatial extent of activity in V1 increases with *perceived, illusory* size.

In summary, the visual system is able to ‘zoom in’ and devote more cortical resources to particular entities in the visual field; the stimulus for such ‘magnification’ is apparent size, as indicated by apparent distance, and a prime cue is vergence angle.

We now apply this established research to reading. Perhaps divergence during reading means that the oculomotor system indicates to the rest of the visual system that a more distant object is being inspected and that more cortical resource should be employed. Employing more cortical resource cannot improve the quality of the visual information entering the lenses, but it *can* improve the granularity of the cortical substrate of the relevant visual processing. It can provide more neurons for the task.

It is harder for readers to distinguish between the basic elements of Chinese orthography compared with English orthography. The ‘basic units’ of Chinese orthography have been claimed to be radicals (Chen, Allport, & Marshall, 1996), those of English have been claimed to be letters (Pelli, Burns, Farell & Moore-Page, 2006). Pelli et al. conclude that participants’ ‘efficiency’ (compared with ideal observers) in recognizing orthographic stimuli (Chinese among them) is inversely proportional to the *perimetric complexity* (perimeter squared over ‘ink’ area) of its basic units and nearly independent of everything else.

Chinese orthography involves visually discriminating between informationally denser entities than does English orthography (Pelli et al., 2006)—just the sort of

orientation processing that Arnold and Schindel (2010) found was improved by an increase in illusory size. Perhaps we should find more divergence (or exovergence) when the reading task would benefit from an increase in visual sensitivity, such that the oculomotor system signals to the rest of the visual system (in a situation—reading from the screen—with no good monocular cues to depth) that the fixated text is farther away, that it is bigger-in-the-real-world and that it is appropriate to invoke constancy, thereby providing more cortical processing resources.

We studied divergence in terms of the crossed and uncrossed FDs at the beginning and end of fixation. We tested two hypotheses. First, that the visual demands of Chinese, leading to smaller saccades and longer fixations, would see smaller FDs at the start and end of fixation. Second, that we would find more divergence in the reading of Chinese than in the reading of English, simulating increased depth to invoke size constancy.

EXPERIMENT

Method

Participants

Participants were 45 English and 46 Chinese native speakers, tested as part of the Edinburgh 5-Language Corpus. All reported having normal or corrected-to-normal vision and were paid for their participation.

Apparatus

Participants were seated in a quiet room with diffused lighting, at a viewing distance of 75 w from a 22" Iiyama Vision Master Pro 514 display. A chin-rest with forehead support kept head position stable. The height of the chair was adjusted so that the eyes were positioned centrally in front of the screen (i.e., the supporting

chin-rest was not moved). Screen resolution was 1024 x 768 pixels. We used an SR Research EyeLink II head-mounted video-based tracker (S-R Research Inc).

Stimulus Materials and Procedure

Eye movements were recorded binocularly, using pupil-only tracking mode, with eye position sampled at 500 Hz, in the reading of English (24 pt monospaced Monaco font) and Chinese (PMingLiU, standard print) texts consisting of 21 newspaper stories in each language, containing about 5000 words, presented on consecutive pages of up to five lines, over some 500 lines. Text was displayed as black characters on a light background. Maximum line length was 64 English characters. Reading direction for both languages was left to right, down the page. Each monospaced English letter was 14.4 pixels (0.43 degrees of visual angle), each Chinese character 28 pixels.

A grid of nine fixation targets was used for calibration. Each eye was calibrated independently by occluding the other eye with a black paper shade. After calibration, participants read two pages of on-screen instructions and then a practice article of four pages in length.

Before each page of text was displayed, a black fixation disc 23 pixels in front of the first word of the first line was displayed for 1500 ms; participants fixated this disc until the page of text appeared. After reading the page, participants fixated on a 11×19 -pixel rectangle below the end of the last line before pressing the keyboard to continue.

Participants responded on the keyboard to one untimed yes/no comprehension question displayed after each story; half of the questions had 'yes' as the correct answer. Before proceeding with the next article, the grid of nine fixation targets was displayed for the experimenter to check that calibration accuracy was good, and if

necessary re-calibrate the instrument. The recording session was divided into three blocks with intervening rest-breaks, and lasted approximately 90 minutes.

In each corpus, we analysed precisely temporally synchronized binocular fixations, RE and LE fixations starting and ending at exactly the same time. This large subset (approximately half of all individual fixations) allows us to address binocularity with the two eyes contributing equally. It excludes most of the data that were outside the area of the text (approximately 3%). No other exclusions were made from this very large dataset.

These data address binocular movement within a fixation, for a large, representative corpus of reading-for-meaning behaviours with multiline text in relatively typical reading conditions (normal room lighting; dark text on light background), with no other pre-processing of the data.

Eye-movement researchers have typically defined a ‘conjoint’ binocular fixation as the eyes fixating points within one character’s width (Liversedge et al., 2006). Much Chinese text typically consists of two-part (‘phonetic complex’) characters, with one (typically ‘semantic’) radical on the left and one (typically ‘phonetic’) on the right, the whole character fitting within a square. Even though the functional units of our orthographic stimuli (English letters of 14.4 pixels and average Chinese radical size of 14 pixels) were fortuitously quite comparable, these orthographies naturally differ in almost every other respect. Thus, we defined ‘conjoint’ objectively as only the very small proportion of binocular fixations on the same pixel.

We did not require to know anything about the accuracy of the registration between the recorded fixations and the particular words of the text, in this study. We needed only to know that a particular fixation occurred during reading. Inaccuracy in binocular calibration or in tracking multi-line text might affect how well we can

distinguish between crossed and uncrossed fixations, however; it might cause a crossed fixation to be incorrectly classified as an uncrossed fixation, for instance. Note, though, that we predict divergence in *both* the crossed fixations and the less numerous uncrossed fixations.

Results

English had 90,766 (48.4% of the data) temporally synchronized binocular fixations (i.e. pairs of fixations) out of a total of 373,700 individual fixations; in the rest, one eye's fixation began or ended slightly earlier. Chinese had 98,367 (50.8%) out of 387,350. Only these data were analysed (although preliminary analyses suggest a similar picture in the inexactly synchronized binocular fixations).

Table 1 shows substantial majorities of crossed FDs in both orthographies at the beginning of fixation. By the end of fixation, these majorities fall slightly in both languages, adding to the uncrossed FDs; this category change requires divergence of the eyes, and it is greater in the Chinese data. (N.B. The small numbers of conjoint fixations involve identical pixel fixations by both eyes. For comparison with other studies, conjoint fixations defined as $FD \leq 1$ English letter-width or 1 Chinese radical-width constituted 15.1% in both languages, and 32.7% for $FD \leq 1$ Chinese character-width.)

Table 2 shows the presence of divergence in greater detail than Table 1's crossed/uncrossed categories. In both crossed and uncrossed FDs, and in the binocular fixations that changed category, the percentage of fixations involving divergence of the eyes is greater in the Chinese data. Convergence shows the converse pattern.

We ran linear-mixed effects models with FD as the dependent variable, four random predictors, a separate intercept fitted for participants, a separate intercept fitted for story, a separate intercept fitted for screen (i.e. page of the text), and a

separate intercept fitted for reading line (on the screen) using the lmer programme in the lme4 (Bates, et al., 2013) package for R (R Core Team, 2012). In our linear mixed effects models, we added a new variable when creating a new model and compared models with and without the new variable. The variable was retained in the new model if the comparison between the two models was significant in a chi-squared test.

Table 3 shows that both language (English vs. Chinese) and fixation (Beginning of Fixation [BoF] vs. End of Fixation [EoF]) are significant in predicting binocular disparity. The interaction between language and fixation is also significant. Disparity is *smaller* by 3.62 pixels at the end of binocular fixations for English readers. That is, the two eyes tend to *diverge*, reducing the crossed FD. Also, Chinese readers tend to have *larger* crossed-fixation disparities than English readers at the beginning of fixations by 3.06 pixels. Most importantly, the disparity at the end of fixation for Chinese readers is *smaller* than expected (given English vs. Chinese and BoF vs. EoF) by 2.27 pixels. That is, for Chinese readers, the eyes *diverge* more than for English readers. This movement can be seen in the overall change in disparities (predicted disparities) in Table 3 where English readers have disparities that start at -40.66 pixels and reduce to -37.04 pixels, but Chinese readers start with disparities of -43.74 pixels and end with disparities of -37.84 pixels.

Discussion

We assumed that fixation disparity (FD) is an adaptive aspect of the totality of eye-movement behaviour, as opposed to being simply errorful. We predicted differential exovergence in the reading of Chinese and English, from two different experimental literatures. First, we tested the hypothesis that the smaller saccades known to accompany relatively dense Chinese orthography would lead to smaller fixation-initial and -final FDs, reflecting more precise fixation targeting. Second, we

extrapolated from research on vergence, illusory size and perceptual sensitivity, to the domain of reading, and predicted more exovergence in Chinese. Neither prediction was fully supported by the data. Instead the data suggest a deeper adaptive role for fixation disparity.

First, we consider overall aspects of the data. The similarity in overall proportions of temporally synchronized binocular fixations (about 50% of all individual monocular fixations) suggests a quantitative generalization across reading even these very different orthographies. The precisely temporally synchronized binocular fixations provided us with specific, convenient subsets of the two corpora; these subsets were still core, representative samples of the corpora. Further exploration is required to see what is going on in the remaining slightly unsynchronized binocular fixations, which range from 2 msec offsets through to monocular blinks.

Overall, the simple proportions of crossed and uncrossed FDs we report reflect the general fixation behaviours observed with the viewing conditions allowed by Eyelink technology (normal room lighting and dark-on-light text) (cf. Kirkby et al., 2008; Shillcock et al., 2010).

The FDs observed were relatively large, even by end of fixation, allowing for RE and LE fixations to be frequently on different words/characters. Binocular fixation of different words has been reported by Liversedge et al., 2006, and Nuthmann and Kliegl, 2009; note that the functional status of word segmentation in Chinese text is still debated. It may be that natural viewing conditions and the added visual and cognitive context of multiline text support relatively flexible fusion and/or less precise visual ‘sampling’ of the text by our skilled readers (cf. Cornell et al., 2003; see Jainta and Jaschinski, 2010, for a discussion of effects on Panum’s fusional area).

We turn now to the two hypotheses tested. Readers of Chinese orthography *did* produce significantly more divergence within fixations, in both crossed *and* uncrossed fixation disparities (FDs) *and* in FDs that changed from one to the other during fixation. Chinese readers also changed FDs from crossed to uncrossed more than the readers of English orthography.

However, the size and distribution of exovergence was unexpected. In our best statistical model of the data, we found that FD in Chinese was larger than FD in English at the *beginning* of fixation and that FD was a closely similar size in both languages by the *end* of fixation. Fixation duration in Chinese tended to be longer than in English (density plots not shown), as other researchers have found.

First, then, we did not find the smaller FDs at the beginning or end of fixation that we considered might accompany the smaller, more precisely targeted saccades and the longer fixations of Chinese reading. Our understanding of fixation disparity in reading Chinese should not be based simply and directly around accuracy of fixation targeting.

FDs in both languages were very closely similar in absolute size by the end of fixation. We conclude that this similarity reflects the physical constraints of the reading task in our experiment, which were the same across the two languages, apart from the actual orthographies themselves. The smaller minimum FDs observed by Jainta et al. (2010) did not have counterparts in the fixation-initial or fixation-final FDs in Chinese relative to English; we conclude that the visual density of Chinese does not have a global effect resembling the effect of horizontal autocorrelation discovered by Jainta et al. in the two fonts of the Roman alphabet they used with their German sentences. It is likely that cultural evolution would have militated against undue ‘stripiness’ in Chinese orthography; however, the prediction remains that

relatively high horizontal-autocorrelation *within* Chinese orthography leads to smaller minimum FDs, probably in the middle region of the fixation duration (cf. Vernet & Kapoula, 2009).

Second, our hypothesis that exovergence elicits greater visual sensitivity by signalling apparent depth, predicted that exovergence should cue the Chinese text to be at substantially greater depth at some point during fixation. However, the data show a larger (mostly crossed) FD in Chinese from the beginning of fixation. The larger FD means that the lines of sight of the two eyes cross *closer* to the reader in Chinese than in English. The reduction of the FD by the end of fixation leads to a very similar FD (and cue to depth) in both languages; there is less than a pixel difference, and even then the Chinese FD is the larger of the two. Thus, there is more exovergence in Chinese reading, but ‘at the wrong end of the processing’ for the depth/sensitivity hypothesis; the exovergence acts to reduce the larger Chinese FD at the beginning of fixation, rather than making it smaller than the English FD by the end of fixation.

Reading behaviours are sensitive to multiple factors, which can only be partly controlled in choice of participants and stimuli (cf. Feng, Miller, Shu, & Zhang, 2009) or partly offset by the size of the dataset. With that caveat, we now theorize about how this statistically robust pattern of vergence behaviour across the two orthographies is adaptive.

We claim that *movement* is at the centre of the explanation of the data. Fixational eye movements—microsaccades, drift and tremor—within fixations are critical to reading, as to the rest of vision (Martinez-Conde, Otero-Millan, & Macknik, 2013). Fixations tend to be longer in reading Chinese than in reading English, (Liversedge et al., 2016), reflecting the greater density of cognitive information in

Chinese. We claim that the larger fixation disparity at the beginning of fixation in Chinese is calculated to accommodate/facilitate this longer fixation.

The expanded fixation-initial FD in Chinese reading, relative to English, guarantees that movement can occur throughout the fixation, allowing continuous activation over the retina. In this way, we see that precision of conjugate binocular fixation *per se* is not the dominant factor determining fixation disparity. The fixations of the two eyes *are* precisely targeted, but rather to set the appropriate FD for the subsequent processing within the fixation, not exclusively to ensure conjugate binocular fixation within Panum's fusional area.

To the extent that informational density of an orthography is relatively stable across text—for instance, Chinese is consistently denser than English—it is possible for the reader to 'set' the FD for that particular reading task, given the prevailing physical conditions (illumination, dark-on-light text, etc). In our English reading data FD on one fixation is highly correlated ($r = .99$) with FD on the next fixation.

What is the final status of the hypothesis that exovergence in reading may be adaptive by signalling increased depth, thereby eliciting size constancy and allocating more cortical resources to the processing? First, we do not suggest that any size illusion should be consciously perceptible. Second, our data show that the typical changes in vergence angle are small, potentially corresponding to only a few cms in 'extra distance' from the viewer in our experiment. However, the visual system is exquisitely sensitive to vergence change; note, also, that as vergence angle decreases, approaching zero, the added apparent depth increases more and more, approaching infinity. We suggest that the decrease in vergence angle seen in crossed FDs during fixation, although relatively small, is at least in the predicted direction and may contribute to the seeming preference for crossed FDs in naturalistic reading

conditions, in that reduction of the FD happens by exovergence in crossed FDs. We thereby tentatively extend the theory of FDs in Shillcock et al. (2010).

In summary, the fixation disparity is computed by the reader so as to allow a binocular fixation in which the two eyes typically converge overall, with a minimum disparity reached at some point between beginning and end (Vernet & Kapula, 2009; Jainta, Jaschinski & Wilkins, 2010) and then on to an appropriate fixation-final disparity. Our data show that it is at the initial fixation disparity that an accommodation is made as to how long the expected fixation will last; for the longer fixation durations of Chinese, a larger initial fixation disparity is planned. The logic of the reading task dictates that the size of the fixation disparity is relatively predictable from the global nature of the orthography, but as Jainta, Wilkins and Jaschinski (2010) show, continuous regulation of vergence during the fixation is required to deal with certain visual aspects of the text. We conclude that adding fixation disparity at the beginning of fixation is adaptive: it may provide horizontal space for the longer (constantly moving) binocular fixation necessitated by the informational density of Chinese and/or it may facilitate the convergence onto a minimum disparity. The data do not support the conclusion that increased disparity at the beginning of fixation (at least, of the order seen in our data) is disadvantageous to reading because it militates against fusion. We suggest that the word recognition procedures of the earlier part of the fixation are not inconvenienced by this disparity and that the convergence in the later part of fixation reflects the needs of binocular saccade planning and execution.

Our approach has been to explore the implications of *disjugacy*—the departure from the assumption that the eyes work simply in tandem, particularly spatially (cf. Cornell et al., 2003; Enright, 1998; Hendriks, 1996; Tyler, 2004). This issue has a long history (e.g. Helmholtz, 1910; Hering, 1977; Mays, 1998; Zhou & King, 1998).

We are led increasingly to an understanding of the eyes as collaborating in complex, complementary ways to generate optimal behaviour for the task in hand.

In conclusion, corpus studies can complement the ingenious, carefully designed and controlled factorial studies using eye-tracking technology, with which Rayner and colleagues created the field of eye-movement studies of reading. This twin-track, interacting approach is converging on rich, interesting phenomena in reading behaviour, and on similarities and differences across readers, across eye-tracking technologies, across tasks, across languages and across orthographies.

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List of Tables

Table 1. FD changes between fixation beginning and end in English and Chinese.

(‘conjoint’ = same pixel)

Table 2. Horizontal vergence of the two eyes in English and Chinese fixations.

(conjoint fixations are excluded)

Table 3. Results of the Linear Mixed Effects model predicting binocular disparity by language (Chinese, English), and by the beginning and the end of the binocular fixation. The interaction term is significant and hence included in the model. Whereas raw pixel values were used in the model calculations, the predicted disparities are also shown in degrees, with negative values denoting crossed-fixation disparities (pixel location: RE - LE).

TABLE 1

	Language	Beginning of Fixation	End of Fixation
Crossed	Chinese	88164	85754
	English	85634	85000
Conjoint	Chinese	56	61
	English	34	45
Uncrossed	Chinese	10147	12552
	English	5098	5721

TABLE 2

Crossed							
	<i>Diverging</i>		<i>Converging</i>		<i>No Movement</i>		
	Count	%	Count	%	Count	%	
English	56391	67.3%	27029	32.3%	348	0.4%	
Chinese	61574	72.5%	22973	27.0%	420	0.5%	

Uncrossed							
	<i>Diverging</i>		<i>Converging</i>		<i>No Movement</i>		
	Count	%	Count	%	Count	%	
English	2045	52.8%	1810	46.7%	17	0.4%	
Chinese	6281	67.1%	3039	32.5%	43	0.5%	

	Crossed→Uncross		Uncrossed→Cross	
	<i>Diverging</i>		<i>Converging</i>	
	Count	%	Count	%
English	1833	60.2%	1214	39.8%
Chinese	3153	80.4%	768	19.6%

TABLE 3

Fixed effects:

Parameter	Model estimate	SE	<i>t</i> value	Predicted disparity (px.)	Predicted disparity (deg.)
Intercept (BoF-English)	-40.66	3.224	-12.61	-40.66	-1.233
EoF (EoF-English)	3.62	0.134	26.95	-37.04	-1.123
Chinese (BoF-Chinese)	-3.07	0.143	-21.42	-43.73	-1.326
EoF:Chinese (EoF-Chinese)	2.27	0.185	12.23	-37.84	-1.147

BoF is Beginning of Fixation; Eof is End of Fixation

Random effects:

Groups	Variance	Standard deviance
Participant	300.420	17.333
Article	10.532	3.245
Screen	5.177	2.275
Line	13.978	3.739
<i>Residual</i>	732.759	27.070

Number of observations: 342098

Participants: 46

Articles: 22

Screens: 9

Lines: 5

List of Figures

Figure 1. Divergence is a source of depth information. Divergence causes the horopter (the intersection of the two lines of sight) to move away from the reader.

Figure 2. Crossed and uncrossed retinal disparities.

Figure 1.

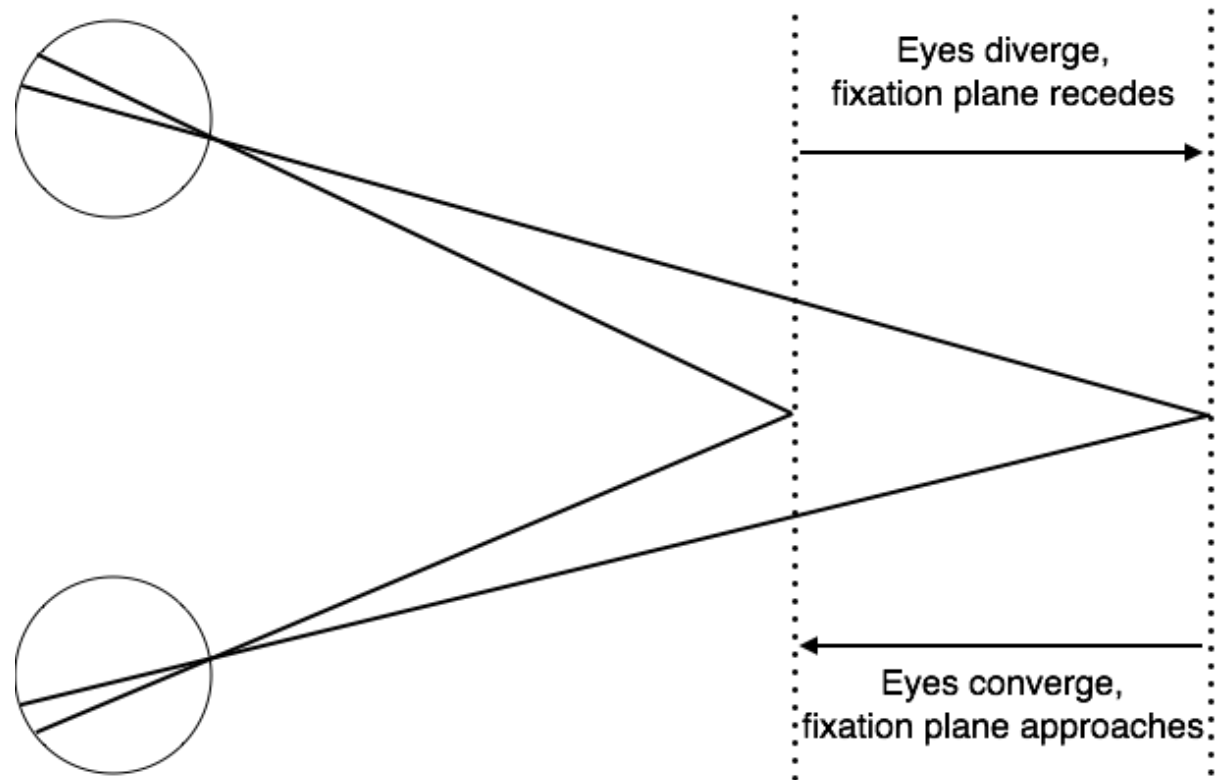
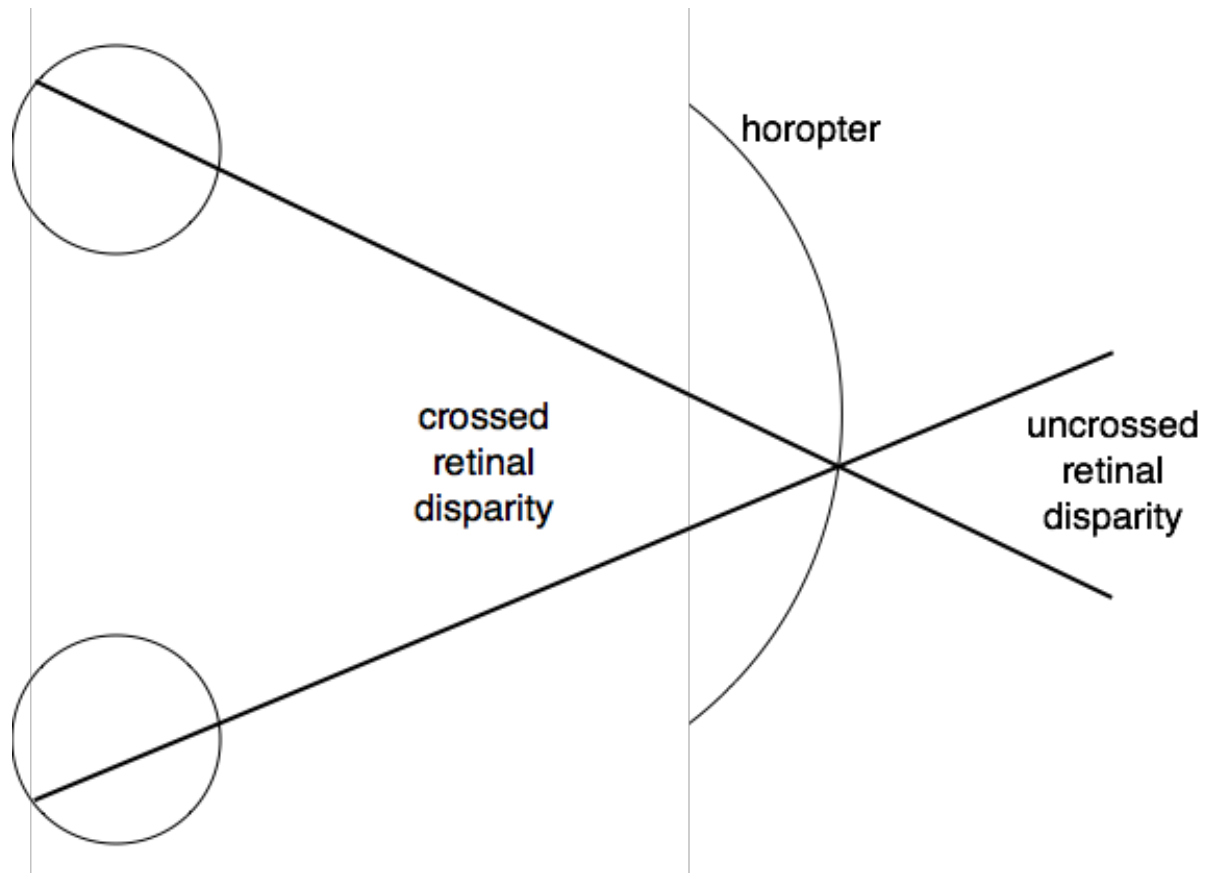


Figure 2.



Footnotes

1. We are indebted to the anonymous reviewers and to Simon Liversedge for extensive discussion regarding this paper.